Laser Induced Fluorescence Measurements in a Hall Thruster Plume as a Function of Background Pressure

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A set of Laser Induced Fluorescence (LIF) measurements in the near-field region of the NASA-173M Hall thruster plume is presented at four background pressure conditions varying from $9.4 \cdot 10^{-6}$ torr to $3.3 \cdot 10^{-5}$ torr. The xenon ion velocity distribution function was measured simultaneously along the axial and radial directions. An ultimate exhaust velocity of 19.6±0.25 km/s achieved at a distance of 20 mm was measured, and that value was not sensitive to pressure. On the other hand, the ion axial velocity at the thruster exit was strongly influenced by pressure, indicating that the accelerating electric field moved inward with increased pressure. The shift in electric field corresponded to an increase in measured thrust. Pressure had a minor effect on the radial component of ion velocity, mainly affecting ions exiting close to the channel inner wall. At that radial location the radial component of ion velocity was approximately 1000 m/s greater at the lowest pressure than at the highest pressure. A reduction of the inner magnet coil current by 0.6 A resulted in a lower axial ion velocity at the channel exit while the radial component of ion velocity at the channel inner wall location increased by 1300 m/s, and at the channel outer wall location the radial ion velocity remained unaffected. The ultimate exhaust velocity was not significantly affected by the inner magnet current.

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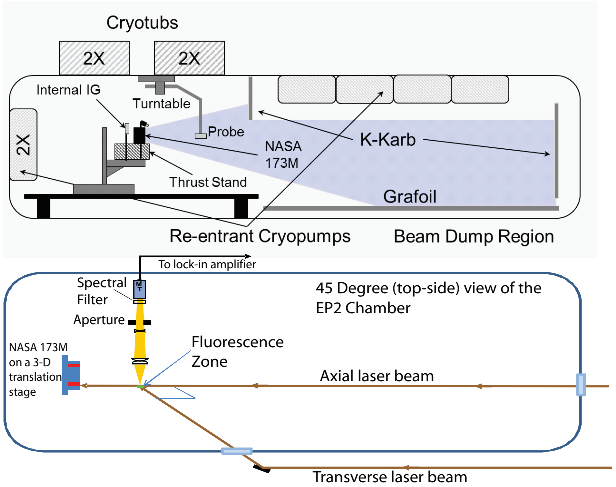

Figure 1. Schematic of the EP2 facility at The Aerospace Corporation. The facility is rated to a pumping speed of 250,000 L/s on Xenon.

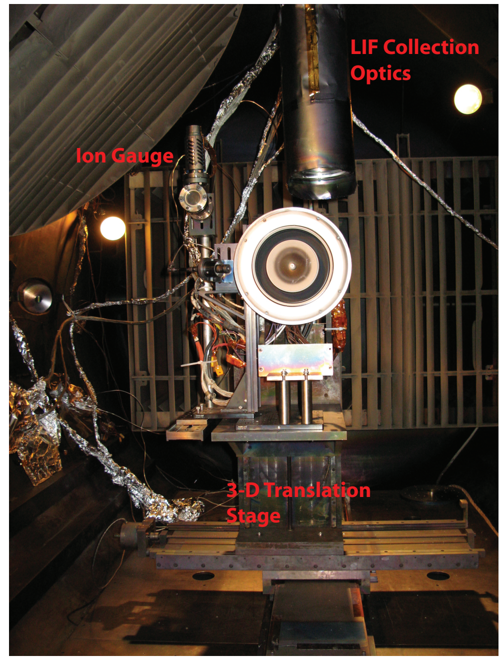

Figure 2. Photograph of the NASA-173M thruster and the LIF setup in the EP2 chamber.

I. Introduction

The problem of the Hall Current Thruster (HCT) performance and plume divergence as a function of the vacuum chamber pressure has recently emerged as an issue of utmost importance for both fundamental research and applied science, and has been generically termed the "facility effects". A number of investigations of these effects have been performed[1–9] but the exact nature and degree of changes to thruster performance appears to be dependent on several factors including the thruster design and operating point. Recently, among other studies, work at The Aerospace Corporation has examined the effect of background pressure on the SPT-100,[7] the BHT-1500,[8] and the NASA-173Mv2[10] Hall thrusters.

Although simple ingestion of the background neutrals may contribute to an increase in thrust with increased background pressure,[11–13] it has been shown that this cannot explain the magnitude of all observations.[2] Several other mechanisms that can also contribute to the observed facility effects have been proposed. These mechanisms include changes in beam divergence and ion acceleration,[7,8] changes in electron coupling in the near-field plume,[5,9] thrust enhancement through the charge-exchange collisions,[14] and changes in the discharge circuit associated with interaction with conductive chamber walls.[6] So far the experimental studies have not produced coherent and conclusive evidence to support a particular mechanism responsible for the facility effects. While we are pursuing fundamental investigations in order to understand this phenomenon, we also continue to catalogue observations on specific thrusters.

To that extent, in this paper we present an experimental investigation of xenon ion velocity distribution function in the near field of the NASA-173Mv2 as a function of background pressure. The data presented here is complimentary to the performance and plume measurements of this thruster that was presented in an earlier paper.[10] The rest of the paper is structured as follows. In section II we describe the thruster details, the facility in which the data were taken, and the Laser Induced Fluorescence (LIF) diagnostic that was used to obtain the ion velocity distribution function. In section III we describe how the LIF data was acquired and processed for further analysis, which, in turn is presented in sections IV and V. Section IV investigates the ion velocity evolution as a function of pressure. Section V analyzes the data as a function of magnetic field. Concluding remarks and summary are presented in section VI.

II. Setup

The NASA-173Mv2 thruster was used to obtain Laser Induced Fluorescence (LIF) measurements of Xe ions as a function of pressure and position in the near plume. The NASA-173Mv1 thruster design and fabrication was a collaborative effort by the University of Michigan and NASA Glenn Research Center (GRC). The NASA-173v2 was designed and fabricated by GRC. Several versions of the thruster were built and extensively tested.[15,16] The NASA-173M Hall thrusters were designed and tested to elu-

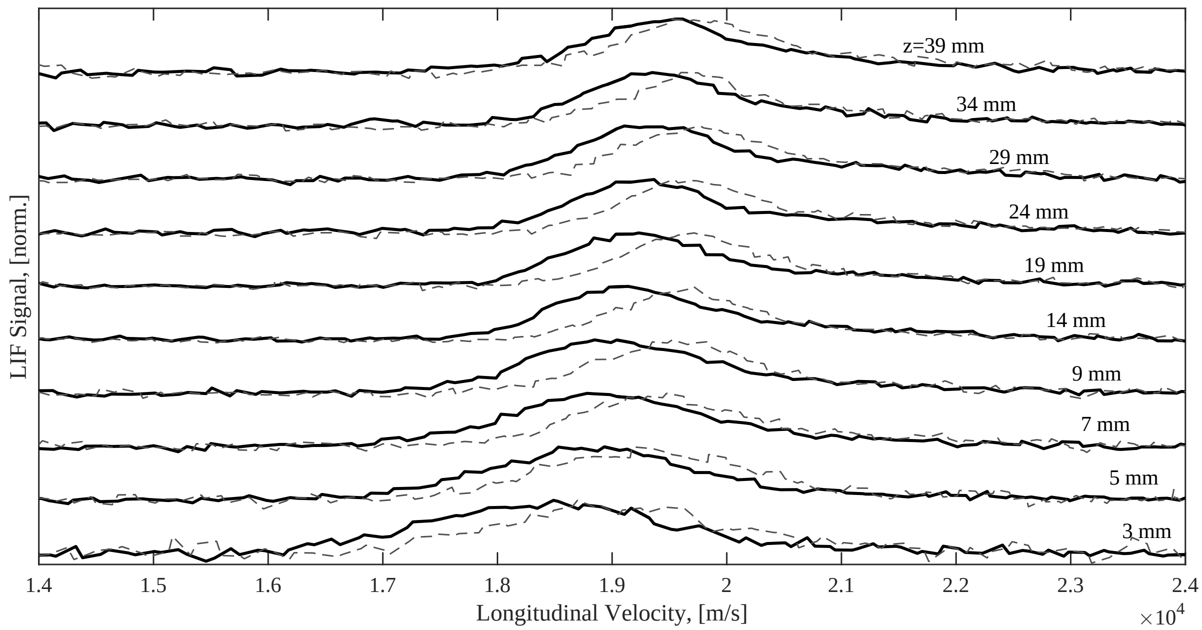

Figure 3. Normalized axial ion velocity distribution profiles at different distances away from the thruster channel exit. The dashed lines correspond to the high background pressure of $\sim 3.3 \cdot 10^{-5}$ torr (2 pumps running). The solid curves correspond to the low pressure of $\sim 9.4 \cdot 10^{-6}$ torr (10 pumps running).

cidate the underlying physics governing Hall thruster operation and performance, and to help overcome design challenges associated with implementation of Hall thruster technology on NASA science missions. They are scaled for operation at a nominal discharge power level of 5 kW. The NASA-173Mv2 thruster is a single-stage thruster with a magnetic lens field topology. The magnetic circuit consists of the magnetic poles, inner and outer electromagnets, and an external trim electromagnet, although the latter was not used for this test. The v2 thruster magnetic field topography was modified to leverage lessons learned during earlier test campaigns that provided insights on how the thruster performance at high specific impulse could be improved with an improved magnetic field topography. The thruster has an outer diameter of 270 mm and total length of 87 mm. The discharge chamber of the NASA-173Mv2 has an outer diameter of 173 mm, a channel width of 25 mm, and a channel depth of 38 mm.

During the reported tests the thruster was operated with laboratory power supplies. After thruster ignition, a 1 hour warm-up period was implemented prior to taking measurements. The facility conditions relevant to the thruster operation, including pressure, propellant flow rates, thruster and thrust stand temperatures, were continuously monitored and recorded. For the reported measurements the thruster was operated at 4.5 kW, 300 V and the ratio of the cathode to anode flow split was maintained at 10%. The nominal inner magnet current was 2.6 A and the nominal outer magnet current was 2.06 A. The thruster was installed on a 3-D translation stage system with the cathode keeper orifice located 19 mm away from the side edge of the thruster at the 9 o'clock position and 12.7 mm in front of the exit plane. The cathode was positioned at an inclination of 30° from thruster centerline with respect to the thruster orientation.

The test described in this paper was performed in the EP2 facility, shown schematically in Fig. 1, at The Aerospace Corporation. The facility has been described in detail elsewhere[7] and will only be discussed briefly here. The chamber is 2.4 m in diameter and 9.8 m long with a total of 10 cryopumps providing a xenon pumping speed of 250,000 l/s. There are 6 re-entrant cryopumps (2 behind the thruster and 4 in the beam dump region) and 4 cryotubs beside the thruster.

Figure 2 provides a photograph of the test set-up. The background pressure with the operating thruster was in the range from $9.4 \cdot 10^{-6}$ to $3.3 \cdot 10^{-5}$ torr. Pressure variation was achieved by operating a different number of pumps. This paper describes the LIF measurements taken by operating 2, 4, 6 and 10 pumps, thus producing four pressure levels for these tests. The pressure was measured by a calibrated, internally mounted, ionization gauge (labeled "Internal IG" in the top pane of Fig. 1). The gauge was mounted on a tee with the entrance aperture facing in the same direction as the thruster exit plane ensuring

that background neutrals would enter both the gauge and the thruster in a similar manner. The tee entrance aperture was located approximately at the 10 o'clock position when facing the thruster and 10 cm behind the thruster exit plane. A photograph of the Internal IG is shown in Fig. 2. All pressure readings reported here have been corrected by a scale factor of 0.348 for xenon relative to nitrogen.

The LIF instrument used in this study was designed to measure two-dimensional velocity profiles of Xe ion and neutral species simultaneously. It is an expanded version of the apparatus previously used to investigate the SPT-140 thruster.[17,18] For this work we used only the Xe^+ portion of the setup. Here a 6000 series New Focus tunable diode laser with the center vacuum wavelength of 834.95 nm (driven by a Vortex controller) excited the $5d^4F_{5/2}-6p^4D_{5/2}$ transition in Xe^+. The laser beam was divided into two components, each of which was sent through a series of mirrors and a telescope to cross orthogonally in the EP2 vacuum chamber, as shown schematically in Fig. 1(b). One beam entered the end of the chamber and measured the axial component of ion velocity; the other entered the side and measured the transverse component. The two beams were optically chopped at different frequencies.

The LIF signal from the $6p^4D_{5/2} - 6s^4P_{3/2}$ Xe^+ transition at 542 nm was collected by a 15 cm lens system and focused through a 10 nm bandwidth interference filter onto a Hamamatsu 955 photomultiplier tube (PMT). The electrical signal from the PMT was divided among two Stanford Research SR830 lock-in amplifiers, each tuned to one of the two chopper frequencies. A Burleigh WA-1500 wavemeter measured the laser wavelength during the laser sweeps. This scheme allowed simultaneous measurements of both components of the Xe ion velocity distribution function.

The LIF data were taken in a rectangular region encompassing the near field of the thruster. Measurements were taken in a grid consisting of ten distinct physical locations along the axis parallel to the thrust vector from 3 mm to 39 mm, as measured from the channel exit, and three locations along the radial dimension: at the channel inner diameter, in the middle of the channel, and at the channel outer diameter.

III. LIF Data

Each data set consisted of 300-point scans and typically covered a frequency range of 40 GHz. Figure 3 displays scans of the axial ion velocity distributions at various axial positions and at the channel inner diameter. Distance from the thruster channel exit is indicated at the top of each curve. Each LIF profile

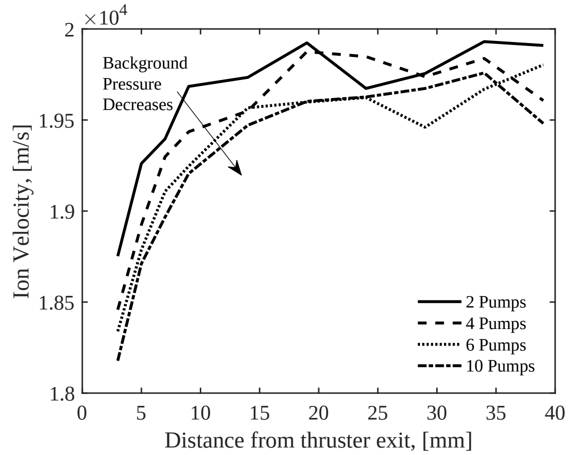

Figure 4. Axial ion velocity profiles (at the channel centerline) as a function of distance from the discharge channel exit at the four measured pressure conditions.

is normalized to its peak. Corresponding radial velocity profiles were obtained simultaneously, but are not shown in order to highlight the difference in the ion velocity evolution at two different pressures. The dashed curves in the figure correspond to the highest pressure ($\sim 3.3 \cdot 10^{-5}$ torr) obtained by operating only two pumps. The solid curves correspond to the lowest pressure ($\sim 9.4 \cdot 10^{-6}$ torr) obtained with all ten pumps running. Measurements at intermediate pressures of $\sim 1.8 \cdot 10^{-5}$ torr and $\sim 1.4 \cdot 10^{-5}$ torr, corresponding to four and six pumps, were also obtained, but are not shown.

The mean ion velocity at each physical location and in each direction was calculated by numerically integrating the first moment of the measured distribution function according to

$$\bar{v} = \int f(v)vdv / \int f(v)dv,$$

and as described in Ref. 19. Velocities presented and analyzed in this work are the mean ion velocities obtained by the method described above. It should be noted that at a few locations, specially near the channel outer wall, poor signal to noise ratio resulted in unreliable estimation of the radial mean velocity. We will point out instances where the calculation was unreliable in the text, as appropriate.

IV. Pressure Effect

Figure 4 shows the axial component of the Xe ion velocity measured at the center of the discharge channel as a function of distance from the channel exit. The four curves in the plot correspond to the four background pressures: $9.4 \cdot 10^{-6}$ torr with 10 pumps, $1.4 \cdot 10^{-5}$ torr with 6 pumps, $1.8 \cdot 10^{-5}$ torr

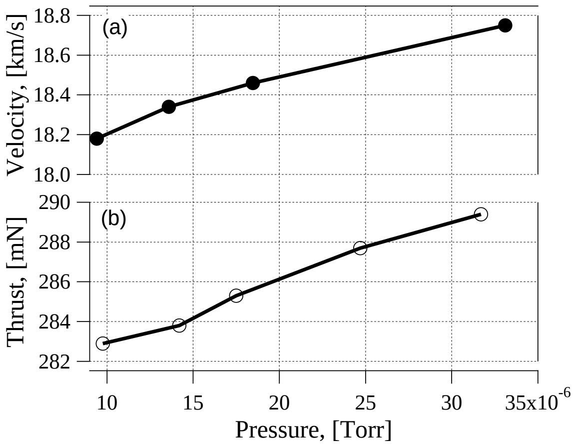

Figure 5. Axial ion velocity at the channel exit, panel (a), and thrust, panel (b), vs pressure.

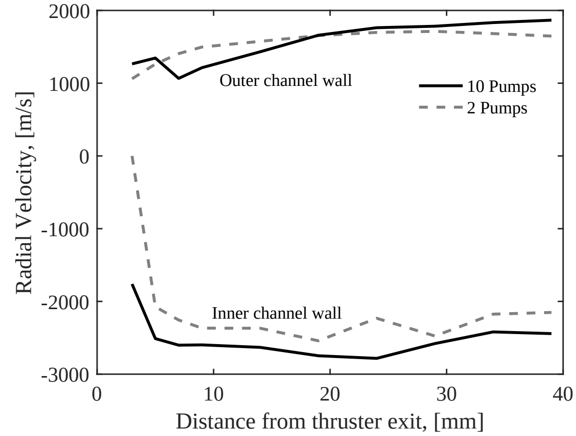

Figure 6. Radial velocity profiles in the plasma plume at the radial locations corresponding to the inner and channel outer walls at two pressure conditions.

with 4 pumps, and $3.3 \cdot 10^{-5}$ torr with 2 pumps.

All four curves show that ions reach the ultimate exhaust speed of 19.6±0.25 km/s at a distance of 20 mm from the channel exit. That ultimate speed is not sensitive to the background pressure within the error of the measurement in the tested pressure range. The data implies, therefore, that the accelerating electric field extends to about 20 mm outside the channel exit and the terminal location of the ion acceleration zone is pressure independent. This conclusion is consistent with the observations by Nakles and Hargus (see Fig. 7 in Ref. 20) where the authors found that for the BHT-600 the ultimate axial ion velocity was achieved at 10 mm from the channel exit and was not sensitive to pressure. It is, however, interesting to observe the findings by Diamant *et al.*[7] that for the SPT-100 the ion accelerating voltage decreased with the decreasing pressure. It is possible that the pressure effects on the accelerating mechanism vary between the different thrusters designs. It is also possible, however, that there exists a discrepancy between the LIF measurements taken in the immediate vicinity of the thruster exit, such as reported here and in Ref. 20 and the RPA measurements, which were the basis for the conclusions drawn in Ref. 7.

Figure 7 in Ref. 20 also shows that, even though the ultimate exhaust velocity is not sensitive to pressure, there is a drastic pressure effect on the axial ion distribution profiles and the mean velocities within the acceleration zone of the thruster. We see an indication of a similar phenomenon in the NASA-173Mv2 data by studying the axial velocities as a function of pressure at the channel exit, which are shown in Fig. 5(a). In this figure the dots correspond to the velocities at the channel exit of the four curves shown in Fig. 4. The figure indicates that a larger portion of ion acceleration occurred inside of the channel as pressure increased. Significantly, in a previous study[10] we reported that thrust also increased with the increasing background pressure. Some of the previously reported thrust data is reproduced in Fig. 5(b) for a convenient comparison with the velocity data. It is interesting to note that over the reported pressure range velocity at the channel exit increased by approximately 3% while the thrust increased by approximately 2% as pressure increased.

The close correspondence in the increase of the exhaust velocity at the channel exit and thrust leads us to speculate on how pressure affects the nature of the force transfer mechanism in a Hall thruster geometry and the location of the ionization and acceleration zones. A simple mechanism for gas ingestion has been described in multiple studies, such as Ref. 11. There, a zero-order effect on thrust was investigated by assuming that a flux of the background neutral gas particles is ionized and is accelerated back out of the thruster, thus increasing the thrust. It is, however, also likely that the ions produced by the background neutrals shift the location of the electric field further inward. Evidence of that is provided in Ref. 20. Since thrust is proportional to the integral of $J \times B$ over the acceleration zone[21] and the location of the magnetic field does not change, it is reasonable to expect that the location of the electric field will strongly influence thrust. This, in turn leads us to conclude that at low pressures, the acceleration zone moves toward the region with a lower magnetic field, downstream of its maximum value.

Diamant *et al.* also attribute thrust decrease at lower pressure to a widening plume divergence. We see only a weak evidence of the pressure effect on

the plume divergence for the NASA-173Mv2. Figure 6 contrasts the radial velocity components along the channel inner and outer walls at the highest and lowest measured pressures. We note here that the measurement at the inner wall closest to the channel exit at the high pressure is unreliable because of the high signal noise. The data show that the radial velocity at the outer wall location does not vary significantly with pressure from 3 to 40 mm away from the channel exit. There is an approximately 500 m/s increase, on average, in radial velocity at the channel inner wall location at the low pressure when compared to the high pressure. The weak dependence of the plume divergence on pressure seems consistent with the plume measurements reported previously for this thruster in Ref. 10.

It is also interesting to note the asymmetry between the inner and outer wall radial velocities. The radial velocity at the channel inner wall location is roughly 1000 m/s greater than at the channel outer wall. This may indicate that the inner coil current may be increased to optimize the beam divergence and possibly improve performance of the thruster. We will investigate the effect of varying magnetic field in the next section.

V. Magnetic Field Effect

The effect of lowering magnetic field near the channel inner wall of the thruster by reducing the current to the inner coil by 0.6 A is shown in Fig. 7. Here we compare the axial and radial velocities at two values of the inner magnet current at the lowest operating pressure, but similar conclusions can be drawn at all four pressure conditions. Solid lines correspond to the nominal inner magnet coil current of 2.6 A, while dashed lines, marked "Low", correspond to 2.0 A operation. Panel (a) in the figure shows the axial component of ion velocity measured at the channel centerline and panel (b) shows radial velocity evolution in the near field of the thruster plume. The radial velocities were measured at the radial locations corresponding to the channel inner and outer walls, marked accordingly in the figure.

The localization of the magnetic field effect can be seen by contrasting the radial velocities at the locations of the channel outer and inner walls in the near field plume. The radial ion velocity at the channel outer wall location is not affected by adjusting the current to the inner magnet coil, as can be seen in Fig. 7(b). On the other the other hand, a reduction of 23% in the inner coil current resulted in an increase in the radial ion velocity at the channel inner wall by roughly 1300 m/s or 47%. Corresponding to this increase in the radial velocity there is a significant

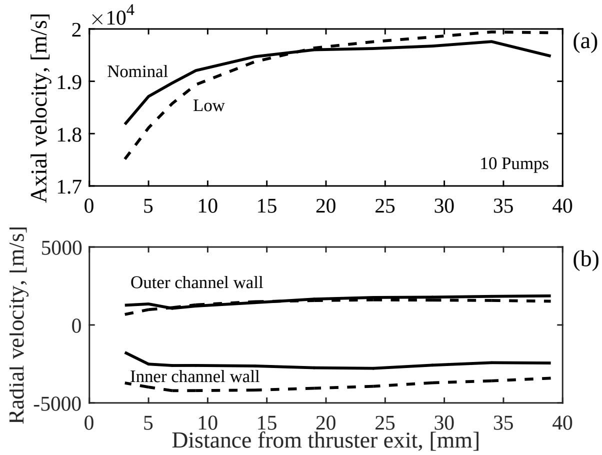

Figure 7. Effects of lowering the inner magnet current by 0.6 A. Solid lines correspond to the nominal inner magnet coil current of 2.6 A, while dashed lines correspond to 2.0 A. Panel (a) shows axial velocity at the channel centerline and panel (b) shows radial velocity evolution in the near field of the thruster plume. The radial velocities were measured at the radial locations corresponding to the inner and channel outer walls.

decrease in the axial velocity within 10 mm of the channel exit, even though the ultimate exhaust velocity of ions seems to be insignificantly changed. The reduction in the channel exit axial component and corresponding increase in the radial component of ion velocity should lead us to the expectation that thrust with the lower inner magnet coil current should be lower than with the default value. The opposite trend was, however, observed in our previous work.[10] This contradiction requires further investigation.

VI. Conclusions

In this paper we presented a set of Laser Induced Fluorescence (LIF) measurements at four background pressure conditions varying from $9.4 \cdot 10^{-6}$ torr to $3.3 \cdot 10^{-5}$ torr. The xenon ion velocity distribution function was measured simultaneously along the axial and radial directions. The measurements were performed in a 10 (thrust axis) by 3 (radial direction) grid corresponding to the rectangular region covering from the channel exit to 39 mm in the axial direction (thrust axis) and from the inner to the channel outer walls. Mean velocities were computed for the two directional components at each measurement location.

Our results showed that ions achieved an ultimate exhaust velocity (velocity component along the thrust axis) of 19.6 ± 0.25 km/s at a distance of 20 mm and that value was not sensitive to pressure. On the other hand, the axial velocity at the thruster exit was strongly influenced by pressure, indicating that

the accelerating electric field shifts inward at higher pressure. This shift in electric field corresponded to an increase in the measured thrust. We found that pressure had a minor effect on the radial ion velocity, mainly affecting ions exiting close to the channel inner wall. At that radial location the radial component of ion velocity was approximately 500 m/s greater at the lowest pressure than at the highest pressure.

Finally, we found that a reduction of the inner magnet coil current by 0.6 A resulted in a lower axial ion velocity at the channel exit. The ultimate exhaust velocity was not significantly affected. Furthermore, the radial component of ion velocity at the channel inner wall location increased by 1300 m/s, while at the channel outer wall location it remained unaffected by the changes in the inner coil current.

Acknowledgements

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